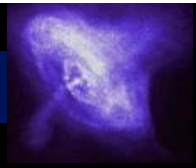

SEXTANT X-Ray Pulsar Navigation Demonstration: Additional On-orbit Results

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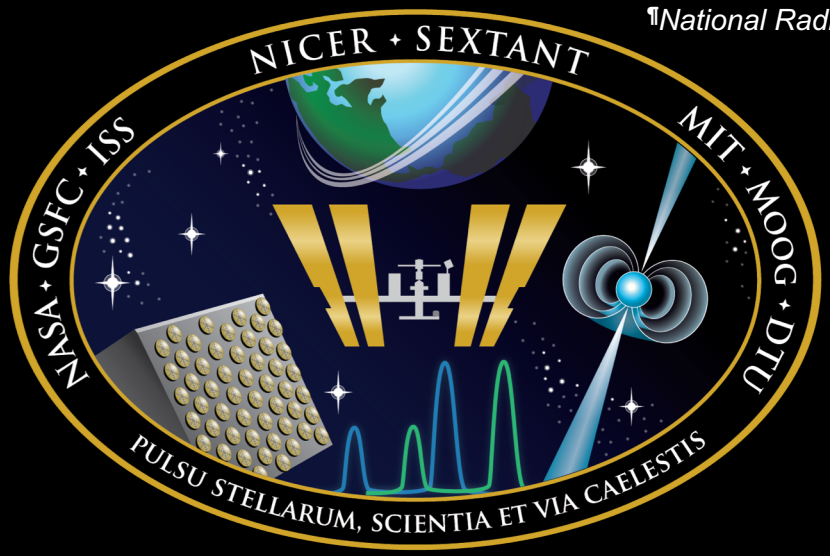

AIAA
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Marseille, France
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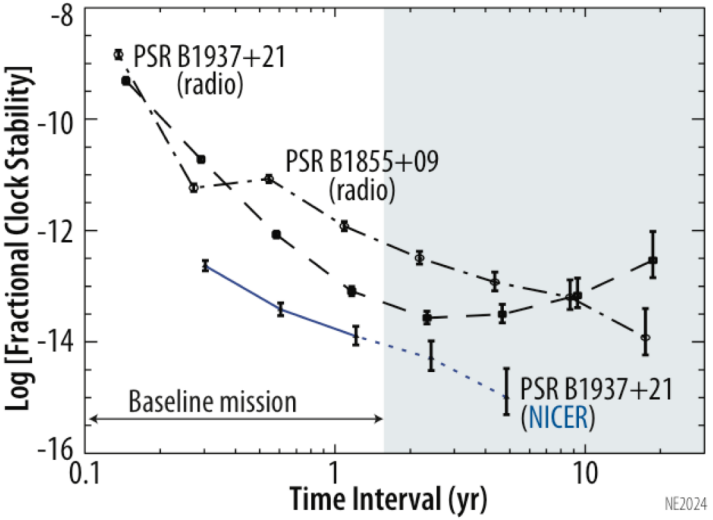
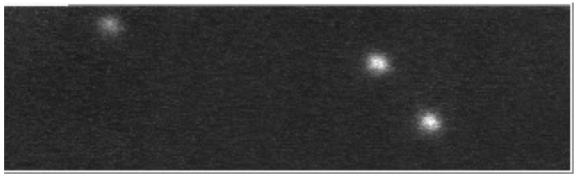
Outline

- X-ray Pulsar Navigation Concept & Background
- Neutron-star Interior Composition Explorer (NICER) mission
- Station Explorer for X-ray Timing & Navigation Technology (SEXTANT) demonstration
- SEXTANT architecture overview
- Review previously demonstrated primary goal
- Recent Experimental Results
  - Navigating with the Crab pulsar
  - Estimating clock bias and rate
- Conclusions & Future Work

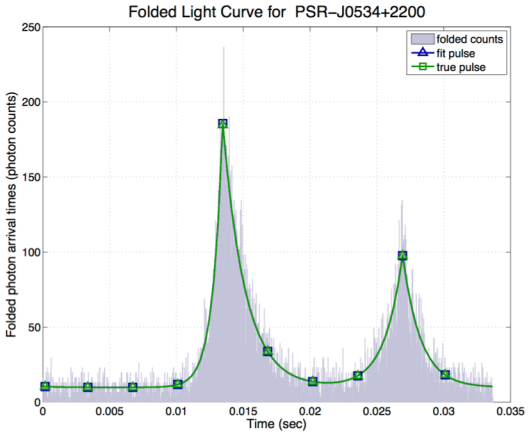
X-ray Pulsar Navigation (XNAV)

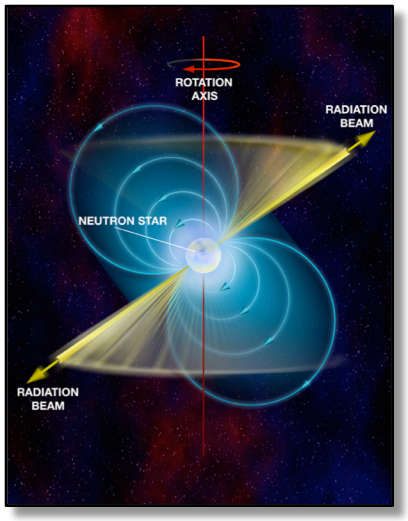
- Millisecond pulsars (MSPs): rapidly rotating neutron stars that pulsate across electromagnetic spectrum
- Some MSPs rival atomic clock stability at long time-scales
  - Predict pulse arrival phase with great accuracy at any reference point in the Solar System via pulsar timing model on a spacecraft
  - Compare observed phase to prediction for navigation information
- Why X-rays?
  - Many stable MSPs conveniently detectable in (soft) X-ray band
  - X-rays immune to interstellar dispersion thought to limit radio pulsar timing models
  - Highly directional compact detectors possible
- **Main Challenge: *MSPs are very faint!***
  - ***Except Crab (PSR J0534+2200)***





Crab Pulsar (1/3 speed), Cambridge University, Lucky Image Group





X-ray pulsar Navigation (XNAV)

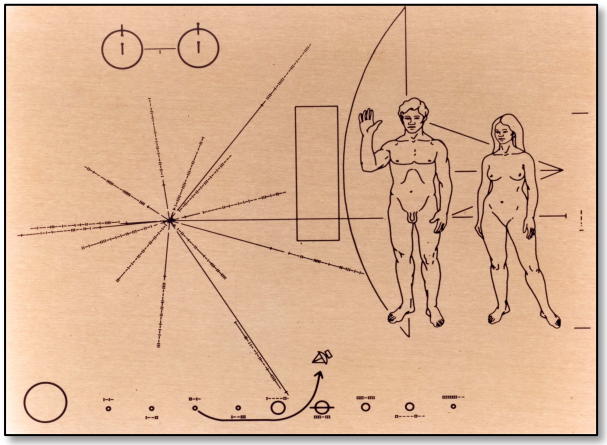
Applications

- Autonomous navigation and timing of uniform quality throughout the Solar System
  - Enabling technology for very deep space missions
  - Backup autonomous navigation for crewed missions
  - Augment Deep Space Network (DSN) or optical navigation techniques
  - Highly available, onboard navigation during periods of limited or no Earth contact, e.g., behind Sun

History

- Pulsars discovered in 1967, immediately recognized as a potential tool for galactic navigation
- US Naval Research Laboratory (NRL) (1999-2000)
  - Unconventional Stellar Aspect (USA) Experiment
- DARPA XNAV, XTIM Projects (2005-2006, 2009-2012)
- Significant body of research (international interest, academic research, several Ph.D. dissertations, etc.)

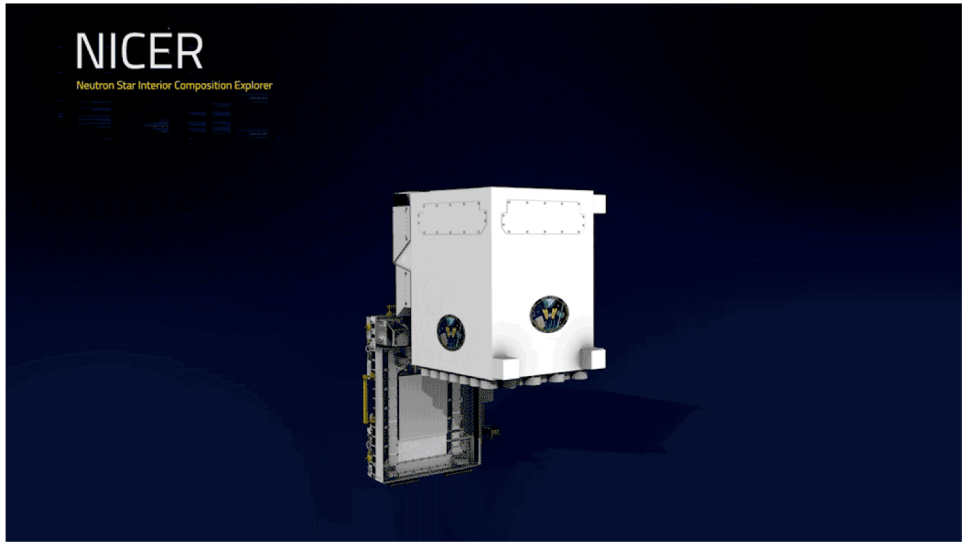
NICER/SEXTANT (2013 selection, 2017 launch) builds on previous work to perform the first in-space, real-time demonstration and validation of XNAV



Pioneer plaque (Pioneer 10,11 1972-73) with Pulsar periods and relative distances to our Sun

Neutron-star Interior Composition Explorer (NICER)

- Launched June 3, 2017 on Space-X CRS-11 to ISS with 18 month nominal mission
  - Additional 6 month Guest Observer program
- X-ray Timing Instrument (XTI) provides unprecedented combination of time resolution, energy resolution, & sensitivity
- Fundamental investigation of ultra-dense matter: structure, dynamics, & energetics
- Determine 4 neutron star radii within 5%, an order of magnitude better than known today
- ***NICER's combination of low-background, large area, precise timing, scalability, & low-cost is nearly ideal for XNAV demonstration***



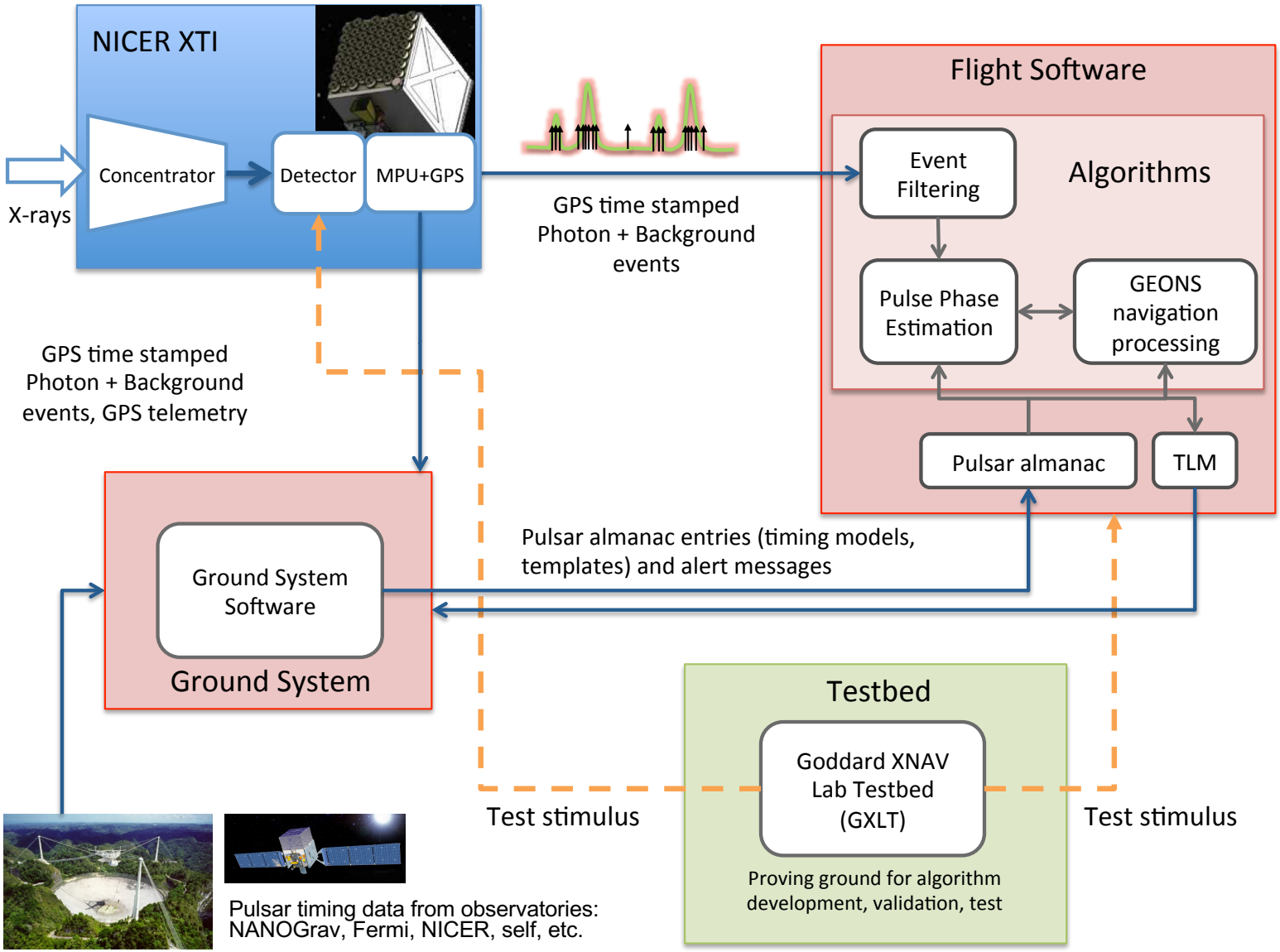
Station Explorer for X-ray Timing and Navigation Technology (SEXTANT)

NASA Space Tech Mission Directorate Game Changing Development funded technology enhancement to NICER

SEXTANT Primary Objective: *Provide first demonstration of real-time, on-board X-ray Pulsar Navigation*

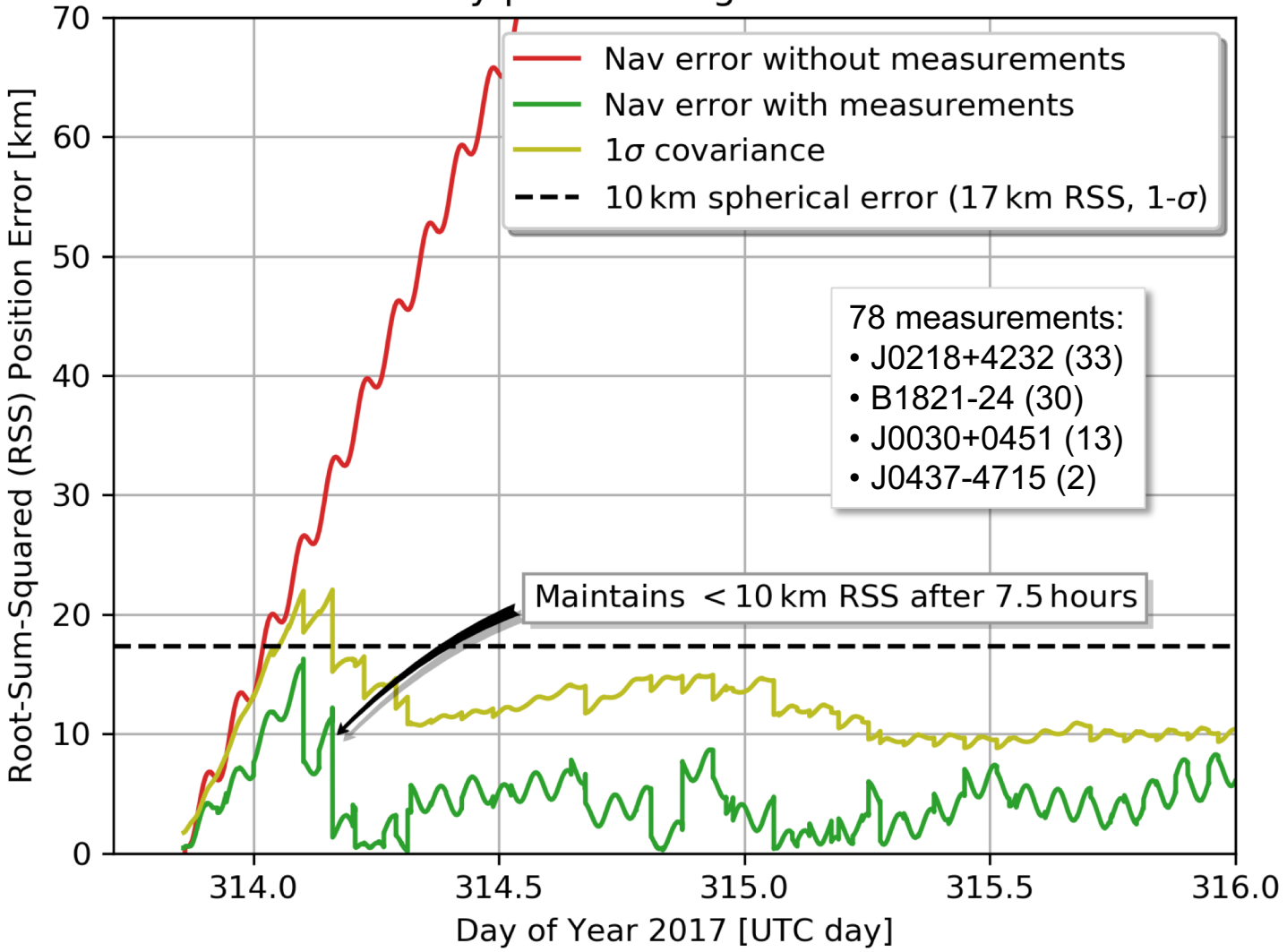
- Implement fully functional XNAV system in a challenging ISS Low Earth Orbit
- Meet 10 km (1 km stretch) performance goal
- Advance core XNAV technologies
- Validate SEXTANT XNAV laboratory testbed (XLT)
- Technology infusion
- In the first 6 months of operation, SEXTANT made great progress toward mission objectives:
  - Completed initial calibration activities
  - Completed multiple successful ground and flight experiments that have met its 10 km performance goal
  - Successfully demonstrated primary objective in Nov 2018, during 2-day experiment
    - See Mitchell et al., *SEXTANT X-Ray Pulsar Navigation Demonstration: Initial On-Orbit Results*, AAS Guidance & Control Conference, 2018, **`https://go.usa.gov/xQXc8`**
- Here we present some additional results beyond the 2-day experiment
  - Crab pulsar XNAV measurement experiment
  - Time estimation bias experiment

SEXTANT System Architecture



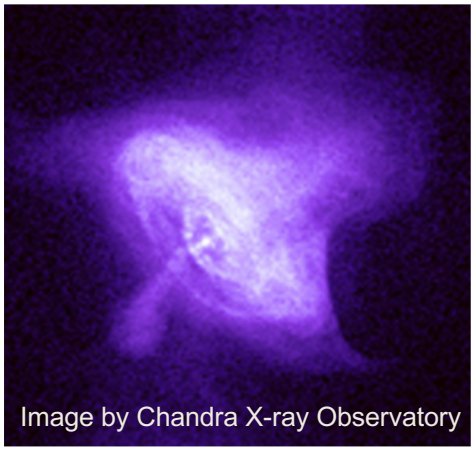
Review of Previously Demonstrated Primary Goal

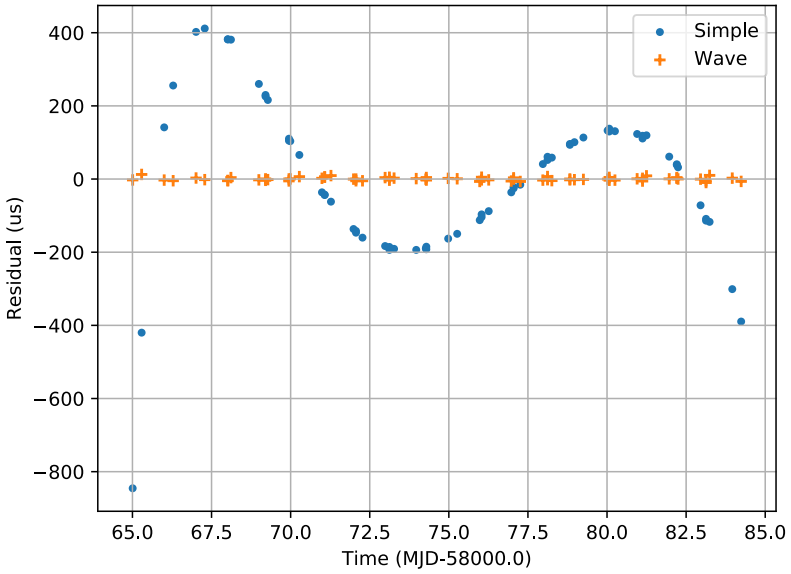
SEXTANT successfully demonstrates fully autonomous, real-time X-ray pulsar navigation on-board NICER



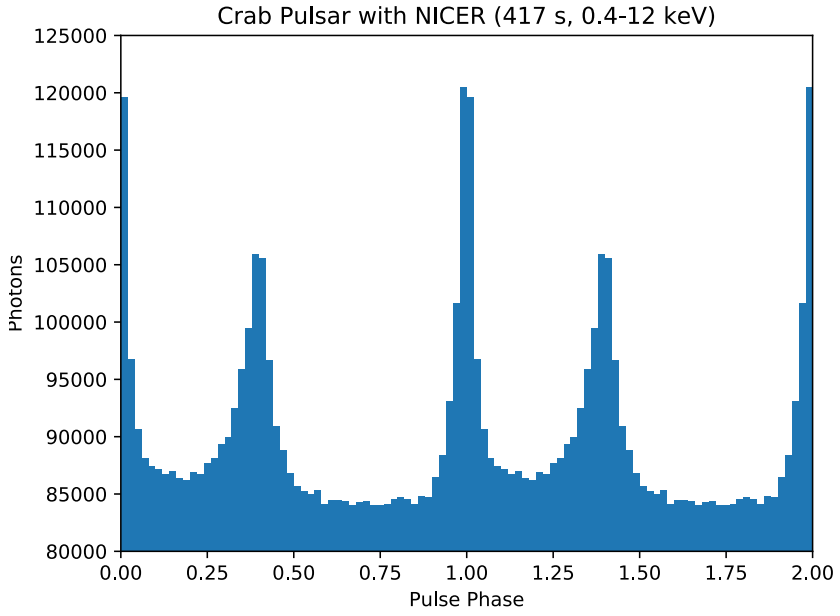
Crab Pulsar (PSR B0531+21)

- Compared to other SEXTANT MSPs, Crab pulsar allows equivalent navigation performance using less observation time, or allows capability for smaller X-ray instruments
  - Crab pulsar flux rates >3 orders of magnitude higher than other SEXTANT MSPs
- Crab requires frequent ground updates (or onboard timing noise estimation) for onboard XNAV
  - Rotationally unstable, so timing model prediction limited to few days (months or years for stable MSPs)
- Alternately, Crab timing model can be accurately determined after-the-fact for use in a post-processing mode





Timing model residuals, pre/post sinusoidal correction fit



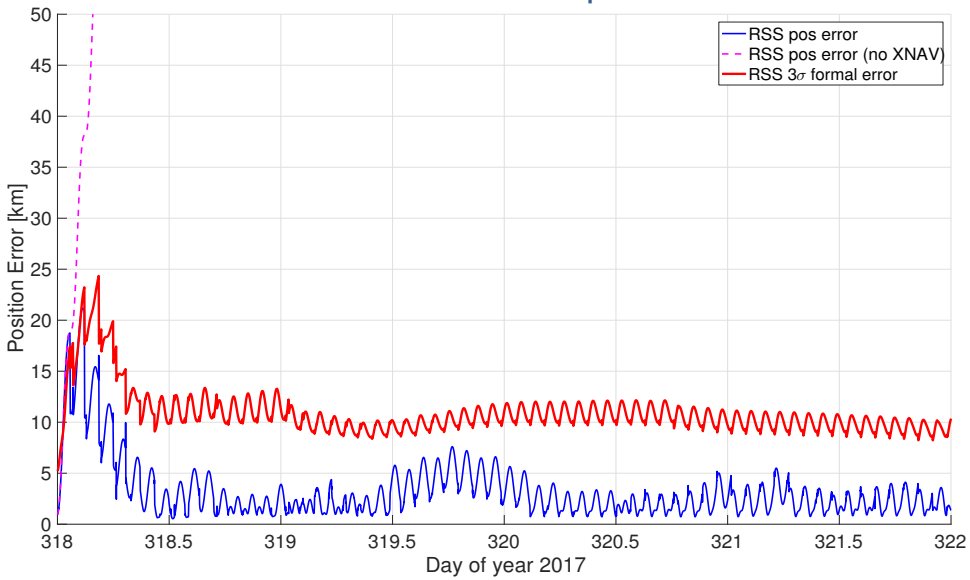
Crab light curve obtained with 417 s NICER observation

Navigating with the Crab Pulsar

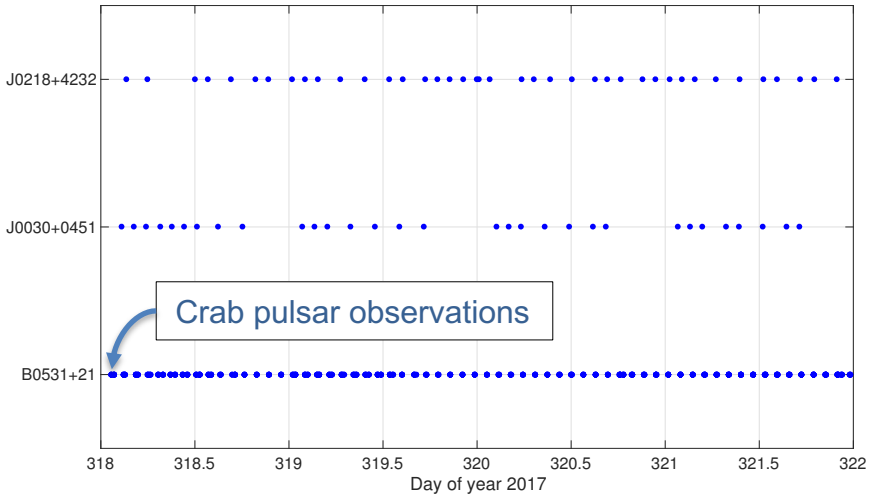
- 2017 days-of-year 318–322 SEXTANT conducted 1st ground experiment using pulsar B0531+21 (Crab)
  - Initialized with degraded GPS state that propagates to >100 km RSS error in few hours
  - Recorded data replayed through ground version of flight software, no clock bias/rate estimation
  - Measurement count: B0531+21 (1119), J0030+0451 (31), J0218+4232 (40)

Errors reduced by XNAV processing to well under 10 km RSS rapidly & maintained for 3 days

XNAV Position Error Compared to GPS



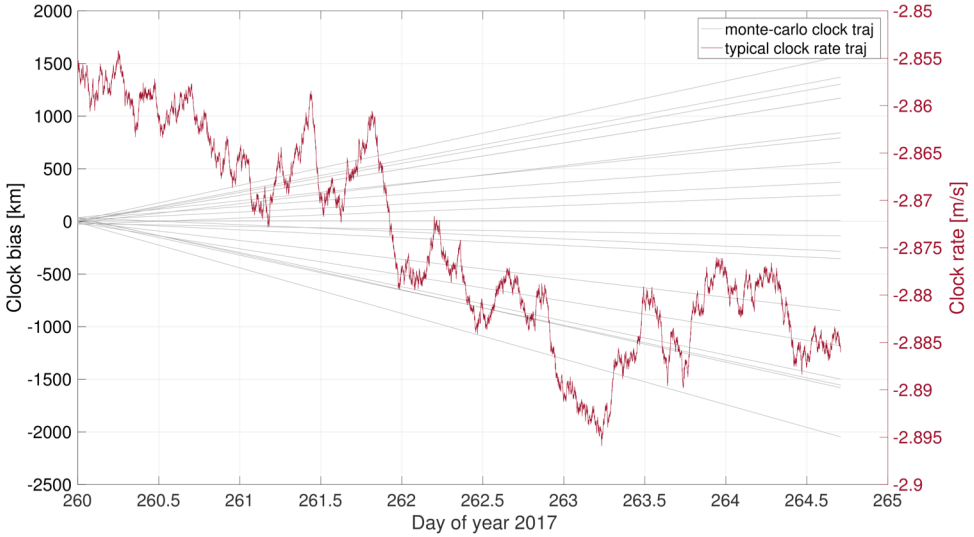
Observing schedule



Time estimation experiment

- *Tested SEXTANT flight software to navigate & simultaneously estimate clock bias and rate*
- Used strong MSP schedule with PSR B1937+21 from 2017 days-of-year 260–264.5
- Used same data for previously reported SEXTANT ground experiment
- Developed augmented navigation filter XNAV measurement model with clock bias & rate estimation
- Simulated clock error trajectories from model of moderate-cost Frequency Electronics, Inc. (FEI) ultra-stable crystal oscillators (USOs) used on NASA's Magnetospheric MultiScale (MMS) mission
- Added clock errors to NICER GPS-timestamped X-ray photon event data

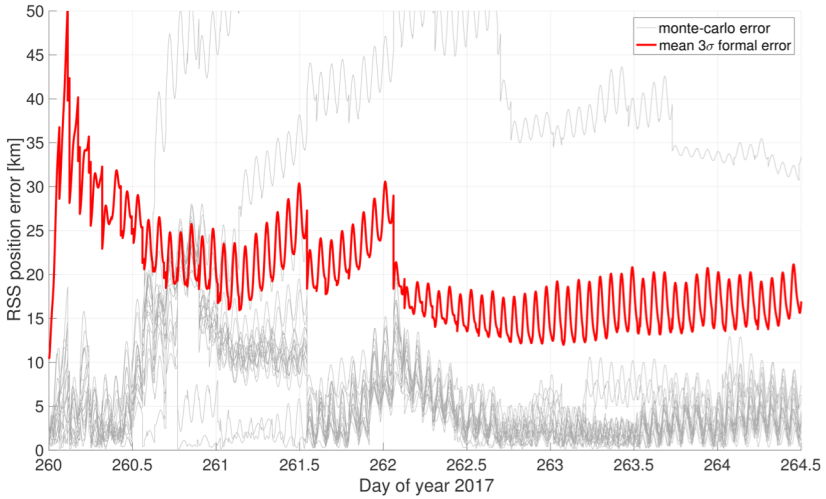
FEI USOs used on MMS

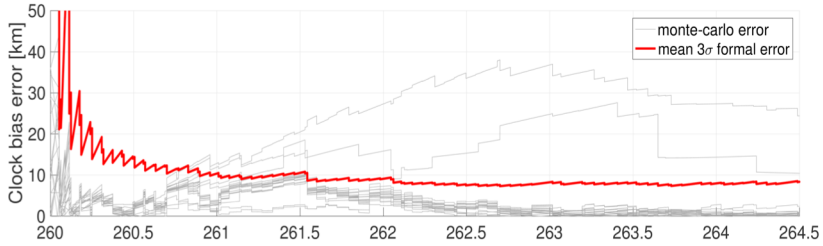


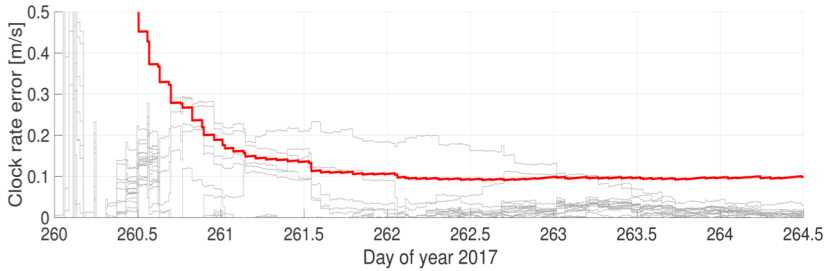
Simulated ultra-stable crystal oscillator clock error trajectories

Time estimation results

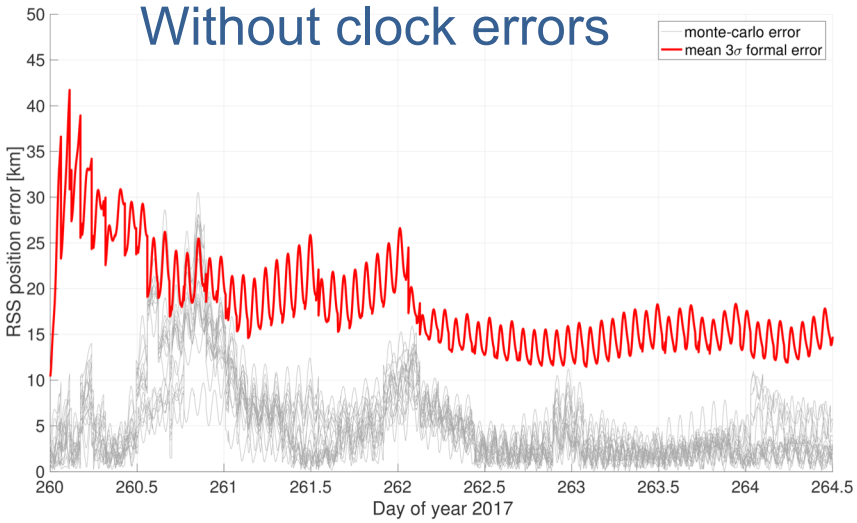
With clock errors







Without clock errors



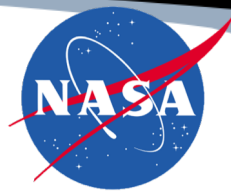
- Methodology: Replay NICER X-ray data with 40 trials through SEXTANT flight software
  - Randomized initial state errors, additive clock errors (20 trials)
  - Randomized initial state errors, no clock errors, no estimate clock states (20 trials)
- Result: Clock is accurately estimated with similar navigation performance
  - Specific cases have an increased chance of divergence
  - Preliminary results, will investigate larger trial set in future

Conclusions

- XNAV is an enabling technology for autonomous deep space navigation & a complement to alternate techniques
- NASA's NICER is the first mission dedicated to the study of pulsars
  - NICER instrument is a superb sensor for XNAV demonstration
- SEXTANT is an attached technology demonstration for first onboard, real-time XNAV use
  - Also advance key XNAV technology components
- SEXTANT has *already* demonstrated feasibility of autonomous in-space XNAV through multiple successful ground and flight experiments meeting 10 km performance goal

- In this paper, we present additional results obtained using NICER/SEXTANT flight telemetry:
  - Successfully processed unique high flux, but rotationally unstable, Crab pulsar
    - Potentially significant benefit for missions needing high-cadence measurements or with small X-ray instrument
  - Successfully estimated position, velocity AND local clock bias and rate estimation possible with moderate-cost/performance spacecraft oscillator
    - **atomic clock *not necessary***

SEXTANT Future Work



- Continue XNAV experiments
  - Flight & Ground experiments
  - Dedicated time for SEXTANT focused observing schedule
- Test & tune current algorithms and develop new ones
- Use SEXTANT XNAV testbed to simulate future applications including deep space trajectories & modeling of reduced size instruments
- Pursue technology infusion opportunities